What domains of clinical function should be assessed after sport-related concussion? A systematic review

Feddermann-Demont, Nina ; Echemendia, Ruben J ; Schneider, Kathryn J ; Solomon, Gary S ; Hayden, K Alix ; Turner, Michael ; Dvorak, Jiri ; Straumann, Dominik ; Tarnutzer, Alexander A

DOI: https://doi.org/10.1136/bjsports-2016-097403

Originally published at:
Feddermann-Demont, Nina; Echemendia, Ruben J; Schneider, Kathryn J; Solomon, Gary S; Hayden, K Alix; Turner, Michael; Dvorak, Jiri; Straumann, Dominik; Tarnutzer, Alexander A (2017). What domains of clinical function should be assessed after sport-related concussion? A systematic review. British Journal of Sports Medicine, 51(11):903-918.
DOI: https://doi.org/10.1136/bjsports-2016-097403

What domains of clinical function should be assessed after sport-related concussion? A systematic review

Feddermann-Demont N, M.D.[1, 2, 3], Echemendia R. PhD[4, 5], Schneider K. PT, PhD[6, 7, 8], Solomon G.[9], Hayden K.A. PhD[10], Turner M., M.D.[11,] Dvorak J., M.D.[2, 12], Straumann D., M.D.[1, 2, 3], Tarnutzer A.A., M.D.[1, 2]

1) Department of Neurology, University Hospital Zurich, Zurich, Switzerland
2) Swiss Concussion Center, Schulthess Clinic, Zurich, Switzerland
3) University of Zurich
4) Department of Psychology, University of Missouri, Kansas City, Missouri, USA.
5) Psychological and Neurobehavioral Associates, Inc., State College, Pennsylvania, USA
6) Sport Injury Prevention Research Centre, Faculty of Kinesiology, University of Calgary, Calgary, Alberta, Canada
7) Alberta Children's Hospital Research Institute, Calgary, Alberta, Canada
8) Hotchkiss Brain Institute, Cummings School of Medicine, University of Calgary, Calgary, Alberta, Canada
9) Departments of Neurological Surgery, Orthopaedic Surgery & Rehabilitation, and Psychiatry & Behavioral Sciences; Vanderbilt Sports Concussion Center, Vanderbilt University School of Medicine, Nashville, Tennessee, USA
10) Libraries and Cultural Resources, University of Calgary, Calgary, Alberta, Canada
11) The International Concussion and Head Injury Research Foundation, London, United Kingdom
12) Department of Neurology, Spine Unit, Schulthess Clinic, Zurich, Switzerland

Corresponding author:
Nina Feddermann-Demont, MD

Swiss Concussion Center
Schulthess Clinic
Lenggstrasse 3
8008 Zurich

Phone: 0041 44 385 7200
Email: Nina.Feddermann@swissconcussion.com

Statistics:
Word count for the text (excluding legends, references & abstract, limit 4500 words): 5372
Word count for the abstract (limit 250 words): 234
Character count for the title (including spaces): 104
Number of figures: 1
Number of tables: 5
Supplementary files/tables: 2/5

Author Note: To the editor-in-chief of BJSM, Dr. Karim Khan, the present paper has been commissioned by Professor Lars Engebretsen and is intended to be part of the BJSM IPHP theme issue on concussion in March 2017. This paper is internally reviewed by the expert group represented at the Berlin Consensus meeting on Concussion in Sport in October 2016

ABSTRACT

Background: Sport-related Concussion (SRC) is a clinical diagnosis made after a sport-related head trauma. Inconsistency exists regarding appropriate methods for assessing SRC, which focus largely on symptom-scores, neurocognitive functioning and postural stability.

Design: Systematic literature review.

Data sources: MEDLINE, EMBASE, PsycINFO, Cochrane-DSR, Cochrane CRCT, CINAHL, SportDiscus (accessed 09/07/2016).

Eligibility criteria for selecting studies: Original (prospective) studies reporting on post-injury assessment in a clinical setting and evaluation of diagnostic tools within 2 weeks after a SRC.

Results: 46 studies covering 3284 athletes were included out of 2170 articles. Only the prospective studies were considered for final analysis (n=33; 2416 athletes). Concussion diagnosis was typically made on the sideline by an (certified) athletic trainer (55.0%), mainly on the basis of results from a symptom-based questionnaire. Clinical domains affected included cognitive, vestibular and headache/migraine. Headache, fatique, difficulty concentrating and dizziness were the symptoms most frequently reported. Neurocognitive testing was used in 30/33 studies (90.9%), while balance was assessed in 9/33 studies (27.3%).

Summary/conclusions: The overall quality of the studies was considered low. The absence of an objective, gold standard criterion makes the accurate diagnosis of SRC challenging. Current approaches tend to emphasize cognition, symptom assessment and postural stability with less of a focus on other domains of functioning. We propose that the clinical assessment of SRC should be symptom-based and interdisciplinary. Whenever possible, the SRC assessment should incorporate neurological, vestibular, ocular-motor, visual, neurocognitive, psychological, and cervical aspects.

Bullet statements

What is already known?

- Sport-related concussion (SRC) is a clinical diagnosis; no single objective test or biomarker has been identified to make the diagnosis.
- Symptoms of SRC are heterogeneous and not specific to concussion.
- Current approaches to SRC assessment emphasize an individualized and interdisciplinary approach.
- The comparison of post-injury test data (symptoms, cognitive test scores, balance) to preseason-baseline data and/or data from non-injured controls is common.

What are the new findings?

- The risk of information bias in SRC-diagnosis is possibly increased due to the variety of health care professionals assessing SRC.
- Reporting is often restricted to the total number of symptoms and/or symptom severity, with detailed information on the type of symptoms often unreported.
- The use of neurocognitive testing in the early time period following concussion is common and more than half of the studies reported significant differences when compared with non-injured controls or individual baseline results.
- Balance testing has been included in some studies, but vestibular and ocular motor systems have rarely been assessed, although preliminary results appear promising.
- Few studies employed an interdisciplinary assessment approach.

Key words: sports, head trauma, signs and symptoms, assessment, preseason baseline testing, systematic review

INTRODUCTION

Sport-related concussion (SRC) is a clinical diagnosis for which no single diagnostic test or biomarker has been identifed.[1] Complicating the diagnostic picture is the fact that the symptoms of SRC vary, occur frequently in non-concussed individuals, are not specific to concussion,[2] (see table 1) and can change unexpectedly and dynamically.[3] A variety of approaches have been used for assessing concussion characteristics with a primary focus on the symptom clusters of cognition, neuropsychiatric symptoms, balance, sleep disturbances, and migraine headache.[4] Other common symptoms such as dizziness/vertigo and visual/ocular motor problems have been studied less frequently.[5]

The variety of symptoms and disturbances associated with concussion necessitates the use of different assessment tests, batteries and strategies, which may help explain why there is little consistency in approaches to the diagnosis of concussion. One area of consistency that does emerge is the routine assessment of cognition with respect to rehabilitation, return to exercise, routine training, and match play decisions.[6 7]

The determination of pre-injury status, mainly through the assessment of neurocognitive functioning, balance, and symptoms at baseline has become popular within the last decade, predominantly in elite sports. The comparison of pre- and post-injury data was designed to identify changes or abnormalities due to SRC. Yet difficulties exist in the appropriate interpretation of test results due to the psychometric properties of the tests and a variety of potential confounding factors (e.g., test conditions, concurrent drug intake, motivation, or quality of test instructions).[8]

/* Table 1 about here */

The aim of this systematic review was to answer the following key questions:

1. What domains of clinical function should be assessed post SRC and what is the evidence for the utility of these approaches?
2. What tools/examination techniques should be used, and when?
3. When is it appropriate to apply pre-injury baseline testing to assist in the interpretation of post-injury test data (e.g. cognitive, balance, ocular motor, etc.).

MATERIAL AND METHODS

Data sources and searches

To address the above research questions, a systematic review of the literature was performed. A literature search (MEDLINE (OVID), EMBASE (OVID), PsycINFO (OVID), Cochrane Database of Systematic Reviews (OVID), Cochrane Central Register of Controlled Trials (OVID), CINAHL (Ebsco), SportDiscus (Ebsco)) was conducted (accessed July 9th 2016) to identify original articles reporting on impaired clinical domains after SRC or sport-related mild traumatic brain injury and their assessment methods. Keywords were first generated by the content expert team (all co-authors), and then adapted by a health sciences librarian (KAH) into a comprehensive search strategy in MEDLINE. The MEDLINE (OVID) search strategy was translated for each database (see Supplementary Table 1). Publications were screened with respect to original data.

Only studies with post-injury assessment in a clinical setting within the first 14 days post-injury were included to better identify acute symptoms by minimizing the overlap with persistent symptoms and the influence of secondary symptoms.[9] Research abstracts from meeting proceedings, PhD theses, unpublished studies, and non-English language studies were not included in the search. Retrospective or prospective studies with five or more injured participants were eligible for inclusion. This review complies with the PRISMA guidelines.[10] A formal review protocol was not registered or posted.

Study selection

Title/abstract and full article screening were performed by two of the authors (NFD, AAT) independently. Discrepancies were resolved by discussion and – if required – by a third reviewer. Articles were selected using the following pre-determined criteria: English language-publications, human population, original research articles, SRC or mTBI as source of injury, data reported on post-injury assessment and evaluation of diagnostic tools within first 14 days post injury, age 13 years or older, and five or more cases (for details see Supplementary Table 2).

Data extraction and quality assessment

After initial assessment of included studies it was determined that the diagnostic approaches varied considerably among studies. Therefore, the first question ("what clinical domains should be assessed to make the adequate diagnosis of SRC"?) was split into two parts. These were: 1) What is the most accurate approach to make a diagnosis of SRC? and 2) "What clinical domains should be assessed to identify optimal intervention approaches for rehabilitation and recovery".

Reports on clinical domains and the assessment methods utilised for concussion diagnosis were considered. Data extraction was performed by NFD and confirmed by AAT. When extracting data from selected studies, the following characteristics were assessed: type of study, participants (including age, gender and sport/level-of-play), times cited in Google Scholar and Web of Science (Thomson Reuters, New York, USA), concussion definition, source/place/time of the diagnosis, assessment components, clinical domains covered, results, and the use of neurocognitive baseline testing. In studies reporting on neurocognitive testing, all tests utilised were identified and assigned to the category that best described the cognitive domain evaluated.

A standardized risk-of-bias assessment was performed using the Newcastle-Ottawa Scale (NOS).[11] The use of the NOS for observational studies has been promoted by the Cochrane Collaboration.[12] The NOS requires rating the selection, comparability and exposure/outcome for a total of nine items (see Supplement 1). Risk of bias was evaluated by NFD and AAT, independently. Discrepancies were resolved by discussion and – if required - by a third reviewer. Risk of bias was rated as "good", "fair" or "poor" (see Supplement 2, Supplementary Tables 3 and 4). Level of Evidence was completed as per the Oxford Centre for Evidence-Based Medicine 2011 Levels of Evidence.[13]

Since the quality of retrospective studies is often poor,[14] and since a sufficiently large number of prospective studies were identified, it was decided to consider only prospective studies for further evaluation (see Supplement 2).

Data synthesis and analysis

Data were extracted and entered into an Excel 2011 (Microsoft Corp., Redmont, USA) spread sheet. A summary of demographic characteristics of the data was performed (total number of athletes, mean age, distribution of sex, type of sport, level of play, and medical background of examiner) to estimate the representativeness of data.

To cover the three predefined research questions, studies were screened for acute post-concussive symptoms reported and diagnostic tests utilized for concussion diagnosis (question 1) and outcome (question 2). A sub-analysis of predominant symptoms was performed for the studies that used a 21 or 22 item graduated symptom scale (question 1 and 2). Since neurocognitive functioning was the domain assessed most frequently, a sub-analysis utilized with respect to domains covered, latency of examination, and outcome was performed (question 2).

Finally, studies that reported comparisons of post-injury test results to: a) individual preseason baseline tests or b) normative values and/or control groups were evaluated (question 3).

RESULTS

Database searches resulted in 6152 citations, of which 2281 were duplicate citations, resulting in 3871 unique citations for screening. Preliminary screening of publication type (editorial, conference, abstracts, etc.) excluded an additional 1701 citations; 2170 citations for abstract/title screening, 89 citations for full-text screening and 46 full-text articles (Figure 1) met inclusion criteria (published between 1995 and 2015 covering 3284 concussed athletes).

/* Figure 1 about here */

There were 33 studies, classified as prospective and included for further analysis involving 2416 athletes of which 87.3% were male (see Table 2).

/* Table 2 about here */

The mean age of the athletes was 17.4 years with the majority of athletes participating in collision sports such as American football (49.3%), rugby (4.9%) and Australian Rules football (5.9%). Most studies took place in American high schools and colleges (n=20, 60.6%). Concussion symptoms in athletes were mainly identified at the sideline (63.7%) by an athletic trainer (54.8%) and in one third of concussions by the (team) physician (12.0%) or team medical staff (21.7%). 30 studies covering 2131 athletes (or 88.2%) provided results of neurocognitive testing, while balance data were available from 682 (28.2%) athletes. Ocular-motor test results were available from two studies (3.6% of athletes).[15 16]

For intra-individual comparisons, neurocognitive preseason baseline testing was performed in 81.8% of studies (reflecting 90.7% of all examined athletes). Neurocognitive testing was combined with a balance test in 25.0% of the studies (see Table 3).

/* Table 3 about here */

Risk of Bias Assessment

NOS ratings were "good" (7-9 points) in 5 studies (10.9%, prospective only n=4 studies or 12.1%), "fair" (3-6 points) in 39 studies (84.8%, prospective only n=28 or 84.8%), and poor (0-2) in 2 studies (4.3%, prospective only n=1 or 3.0%). Reasons for lower scores and higher risk of bias varied between studies but included factors related to selection, measurement, and confounding factors. In many cases, the selection of exposed and non-exposed cases came from different communities[15 17-29] or were not specified.[30-38] A lack of matching of exposed and non-exposed cases to control for age, sex/gender, education, handedness, pre-injury or level of play also commonly occurred.[7 15-18 20 21 23-29 39-50] Additionally, lack of valid measurement tools and threat of recall bias through self-report or potential for expectation bias through an unblinded assessment[7 22 44] were all common sources of systematic error (see Supplementary Tables 3 and 4).

Level of evidence of the prospective studies was considered low with most studies (n=25, 75.8%) classified as level 4 evidence, 7 studies (21.2%) as level 3 evidence and only 1 study[34] (3%) as level 2 evidence.

A total of 39 different (standardized) questionnaires and test batteries (on average 2.5 tests/instruments per study) were identified among studies that employed a post-injury examination. These measures included 11 symptom scales, assessment of neurocognitive functioning via computerized tests (CNP, n=5) and traditional Paper and Pencil tests (P&P, n=17), balance (n=4) and ocular motor function assessments (n=2) (see Table 1).

Symptoms

Posttraumatic symptoms were reported in 28/33 (84.8%) prospective studies. The number of symptoms assessed via standardized scales or questionnaires varied between 7[45 46] and 24[34] items (see Table 4a). Nineteen studies (covering 1618 athletes) reported on symptoms assessed by the Post Concussion Symptom Scale (PCSS, 21 or 22 items).[51] The average post-injury total symptom score using the original form of the PCSS (information provided by 12 studies)[4 7 15 23 29 36 41 42 44 48 52 53] ranged between 8.5[7](<24 hours) and 45.6[52](24-48 hours). Only 3 studies[32 33 48] provided information on average total number of symptoms with scores ranging between 8.3[33] (> 48 hours) and 20[32] (24-48 hours) (see Table 4a).

/* Table 4a about here */

Detailed information on specific symptoms endorsed by athletes was available only for 2 studies.[44 53] Although symptoms varied, the most frequently endorsed symptoms (see Table 4b) reflected issues with alertness/attention (n=165 athletes, 3 items pooled), dizziness/balance (3 items pooled, n=151 athletes), headache/migraine (n=161 athletes, 4 items pooled), and consciousness/awareness (n=152 athletes, 3 items pooled). Turning to individual symptoms, headache (n=70, 71.4%), fatigue or low energy (n=62, 63.3%), concentration problems (n=60, 61.2%), dizziness, drowsiness and feeling slowed down (each n=58, 59.2%) were frequently described, followed by fogginess (53%, 54.1%) and memory problems (n=47, 48.0%). Neck pain was not reported in any of the studies (see Table 4b).

/* Table 4b about here */

“Dizziness” and “fogginess” were associated with a higher total number of symptoms and prolonged recovery[42 54 55]. Houston and colleagues e.g. demonstrated that 10 days post-injury the average symptom level (3.4±8.4) decreased below the pre-injury level (11.0±13.1).[41]

Schmidt and colleagues recommended the graded symptom checklist as a core component of any pre-season or pre-participation test, since it is easily administered, inexpensive, unaffected by group administration, and provide an individualized measure of self-reported symptoms.[50]

/* Table 4a and 4b about here */

Neurocognitive Testing

Thirty prospective studies included CNPs tests for post-concussion assessment. The CNPs utilized were ImPACT (Immediate Post-Concussion Assessment and Cognitive Testing, n=16, NOS rating: good n=3, fair n=13),[4 15 16 19 21 23 29 30 32 33 35 36 42 52 53 56] CogSport (Cogstate Concussion test, n=6, NOS rating: fair n=6),[34 35 43 46 53 57] ANAM (Automated Neuropsychological Assessment Metrics, n=1, NOS rating: fair),[50] Headminder (n=1, NOS rating: fair),[30] and CANTAB (Cambridge Neuropsychological Test Automated Battery, n=1, NOS rating: fair),[25] while three studies used two different batteries in the same study (NOS rating: fair.[30 35 53] Moreover, 16 P&P tests were identified and utilized in nine studies (NOS rating: good n=1, fair n=8),[7 22 25 30 34 46 57-59] while five studies reported on results of the SAC (Standardized Assessment of Concussion; NOS rating fair: n=4, good: n=1).[41 45 47 48 58]

The test batteries generally assessed executive function, attention, learning and memory. CNP baseline tests were available in the majority (n=24) of studies (see Table 1). Of those studies that compared concussed athletes to controls (n=12), significant group differences ($p < 0.05$) were found were noted in more than half of studies. Group differences were found in memory and learning (58.3%), executive functioning (54.5%) and attention (50%). When compared to individual baseline data, significant differences ($p<0.05$) were reported in fewer studies.

Among these studies differences were found in attention (36.4%), memory and learning (32%), and executive functions (20%) (see Table 5). Fogginess was associated with reduced memory performance and slower processing speed) in one study.[42]

Two studies reported on differences in symptomatic vs. asymptomatic athletes after concussion with respect to neurocognitive test results.[19 57] Fazio and colleagues[19] identified significant ($p< 0.01$) impairments in composites scores of verbal memory, visual memory, reaction time and processing speed in both groups, but the asymptomatic group demonstrated better scores than the symptomatic group. Significant ($p< 0.01$) post concussion decline of simple, choice, and complex reaction times of the symptomatic group compared with the asymptomatic and control groups was reported by Collie and colleagues.[57]
Comparing the baseline approach with the normative method has demonstrated significant advantages of the baseline method with respect to simple reaction time ($p=0.043$), while mathematical processing was significantly assessed more accurately by the normative comparison method ($p= 0.001$).[50]

/* Table 5 about here */

Balance
Nine prospective studies presented data on balance by using the (modified) Balance-Error-Scoring-System (BESS, included in the SCAT as the balance test, n=7, NOS rating: good: n=1, fair n=5, poor n=1)[33 37 58], the Sensory Organization Test (SOT, n=3, NOS rating fair n=3).[30 37 40] or the Health`s Balance Accelerometer Measure [60] apart from BESS (NOS rating poor).[20]

Studies on the BESS mainly reported the total BESS score,[20 40 41 58] One study reported data on the 6 BESS individual stance conditions[20] and found significant differences ($p< 0.01$) for the tandem gait (firm/foam) among athletes with SRC when compared to healthy controls. In the other studies, BESS differences between concussed athletes and controls were either not reported or unclear. Significant post-injury differences (each $p<0.01$) for the modified BESS (SCAT) were identified in one study.[48] BESS balance deficits in concussed college football players were described immediately after the injury with a gradual improvement within several days.[17] Houston et al.[41] identified an association between BESS score and health-related quality-of-life measures 72 hours post-injury.

The BAM was classified as not as effective in identifying abnormal postural control compared with the BESS[20].

Broglio and colleagues[30] reported impairment in the SOT composite score in 36.5% (23/63) of concussed athletes. Significant differences were identified in the SOT composite score of concussed athletes when compared to baseline ($p=0.037$) and non-injured control group ($p=0.025$), detectable up to 14 days post-injury.[40]

An (indirect) ocular motor test (King Devick) was included in one study (NOS rating fair)[16] that evaluated nine concussed high school football players. This test demonstrated a significant increase in reading time (p=0.001) when comparing immediate (<30min) post-injury results to individual pre-season baseline-tests and to non-concussed controls. Near point convergence was compared to performance on a CNP in one study (NOS rating fair), which revealed that impaired convergence was associated with significant impairment on verbal memory (p=0.02), visual-motor speed (p=0.02), and reaction time (p=0.001),) in concussed athletes and was associated with a higher total symptom post-injury score (p=0.02).[15]

DISCUSSION

The literature was reviewed to address the following question: Which clinical domains should be assessed post injury? Additional areas of focus included examination of the empirical evidence underlying various assessment approaches (aim 1), the appropriate tools/examination techniques to assess these domains (aim 2), and the contribution of baseline testing (aim 3).

Summary of included participants – representativeness of data

Currently, the literature on the diagnosis of SRC is mainly representative of adolescents and young adult male high school or college athletes who are participating in collision sports, but not for amateur or elite adult athletes. The high frequency of adolescent and young adult athletes might be explained by the large number of athletes participating at these levels, while for other levels (elite, amateurs) either access to the players might have been more difficult, funding may have been more limited, or medical coverage non-accessible. While for elite athletes certain limitations identified here might be less relevant (e.g. lacking initial assessment by the team physician),[32 33 41] future studies focusing on elite (male and female) athletes should be initiated to further address these questions.

Of the 2416 athletes in the included studies who received a diagnosis of SRC, almost half were involved in American football. This might be explained by the high risk for SRC in American football and the popularity of this sport in the United States, or simply that greater research has been devoted to this sport.[61 62] The number of athletes involved in other collision or non collision sports (e.g. rugby, ice hockey or football / (soccer) who were diagnosed with SRC was much smaller (<6% per sport), which necessarily limits conclusions that can be made regarding SRC in these sports.

Likewise, only 12.7% of all concussed athletes included in this review were female. At first sight, this observation was unexpected, since the incidence of concussion may be higher in women,[63 64]. However, females typically do not participate in American football and this may be reflected in the reportedly lower numbers of active participation of female athletes in collision sports.[64 65]

Among the studies reviewed the initial diagnosis of SRC was made at the sideline based on the results of a symptom questionnaire. In the majority of athletes (54.8%) this diagnosis was made by an athletic trainer, and less frequently by team physicians or other health care providers (37.6%). In light of this variability the accuracy of sideline diagnosis of concussion should be interpreted with caution. However, it is unclear how many teams had a dedicated team physician and whether athletic trainers actually diagnosed SRC or removed an athlete from play due to suspected concussion. Fuller and colleagues[35] reported on 26/81 (32.1%) cases in rugby players, where the initial diagnosis of concussion (made by a physician or other) was not confirmed in the follow up examination in a clinical setting.

The risk of bias was fair in most (84.8%) of the prospective studies reviewed. Limitations in study designs were noted in several studies. Underpowered studies may have resulted in a type II error, where a difference was not detected when in fact one does exist.[16 19 22 25 34 40 46] Selection bias may have resulted in a systematic difference in the test values based on the inappropriate selection of controls, resulting in a potential overestimate in test scores.[19 40] A variety of assessment tests were administered by a number of health care professionals with different backgrounds. This may have resulted in a misclassification of test results and has the potential to result in an over- or underestimate of test scores, thus misinforming the true value of a test. In the studies that required retrospective recall, recall bias may have resulted in an overestimate of symptom reporting, or alternately an underreporting of symptoms in some cases. This may also have been the case for the diagnosis of concussion, as the gold standard of diagnosis is a clinical evaluation. There is a lack of objective clinical tests in many cases, thus misclassification of test outcomes may have occurred and resulted in an under or overestimate of the true outcome of a test. These threats to internal validity impact the strength of the ultimate conclusions made by the systematic review.
Consequently, future prospective studies should use a standardized definition of concussion. Case-control or cohort studies that aim at diagnostic accuracy and take into account potential distractors (e.g. previous history of concussion, the effects of exertion/time since cessation of activity, time of day, fatigue, etc.) that may alter the outcome on such tests are urgently needed.

Most studies that reported post-injury assessment in a clinical setting had a strong focus on neurocognitive testing, while other assessment approaches (including vestibular, ocular motor or cervical complaints) were rarely addressed. Since SRC is a complex injury, and often accompanied by concomitant injuries, an interdisciplinary approach to evaluation and treatment is warranted. While ideal for good patient care, interdisciplinary teams also bring together a heterogeneous group of healthcare professionals with different areas of expertise and different levels of training that may lead to varying levels of reliability in the diagnosis and treatment of concussion. For this reason, standardized testing methods and the adoption of a single definition of SRC that is accepted across disciplines and applied uniformly within healthcare disciplines is recommended.

The variability in concussion-related symptoms underscores the need for comprehensive interdisciplinary evaluation

This review confirms previous findings that symptoms of concussion are heterogeneous, not specific and can sometimes even be misleading.[66] The average total number of symptoms and the average symptoms severity score post-injury varied considerably amongst studies. The highest number of symptoms and total symptom scores were observed between 24 and 48 hours post injury. It was surprising that most studies focused on the total number of symptoms (and the total symptom score) instead of the type of symptoms since symptoms typically guide the diagnostic decision and therapeutic management.[66] Since few studies provided symptom-specific data, the interpretation of total symptom scores is challenging.

The most prevalent symptoms reported by the athletes in studies using the PCSS, were headache (71.4%), fatigue or low energy (63.3%), concentration problems (61.2%), dizziness, drowsiness and feeling slowed down (each 59.2%), fogginess (53%) and memory problems (48.0%). While the assessment of memory function is typically included in CNPs (to varying degrees) and frequently was utilised in our study samples, information on the detailed assessment of other potentially relevant symptoms like headache, fogginess or dizziness was very limited. Only two studies added symptom-specific questionnaires,[41 48] although it is well known that specific symptoms like headache,[67] dizziness[54] or fogginess[42] influence some neurocognitive components and symptoms impact on recovery.[19 57] Greater emphasis is needed using symptom-specific diagnostic approaches for the evaluation of these frequently occurring symptoms, particularly in cases of prolonged or atypical recovery.[45 67 2 68 69]

Headache is reported to affect most athletes after SRC within the first few hours of injury, with one study reporting headache endorsement in up to 96% of all athletes.[45] An accurate diagnosis of headache is critical to differentiate migraine or tension-type headaches from those caused by cervical spine dysfunction or musculoskeletal injury.[67] An inaccurate diagnosis may result in inappropriate/missed treatment and therefore increases the risk for a prolonged recovery. Collins and colleagues[70] identified, that 7 days after concussion, athletes with headaches experienced a large number of other postconcussion symptoms compared with athletes without headache (p= 0.001). Similar to headache, causes for dizziness and balance problems are multifaceted, which is reasonable given that maintaining balance requires appropriate integration of three distinct sensory systems (sensory-motor, visual and vestibular).[71] The vestibular system has a high degree of plasticity and can compensate for posttraumatic functional disturbances causing dizziness and vertigo. It is fundamental to identify the impaired sensory system to ensure appropriate posttraumatic management.[7 30 68] While the vestibulo-spinal aspects have been assessed by different balance tests (BESS, SOT), the vestibulo-ocular pathways have typically not been included in concussion management, although promising results were reported in different studies, that did not fulfill inclusion criteria due to latency of assessment (>90 days post concussive event),[34] publication after the date of the systematic literature search,[72] or covering non sports-related mTBI.[68 69]

The presence of dizziness can influence the total number of symptoms,[2 73] is associated with a more than six times greater risk for protracted recovery,[69 72] and might influence neurocognitive performance.[42] Therefore, to the extent possible, a standardized vestibular and ocular motor screening examination should be included in existing screening and testing batteries.[68] A symptom-based, detailed, and interdisciplinary examination by sports medicine clinicians experienced in concussion management should be initiated in athletes with recovery exceeding the typical recovery duration of 14 days. Moreover, it was striking, that none of the studies reported on neck pain despite being a frequent concomitant injury after a head trauma, as has been commonly identified following concussion in different studies, which did not meet inclusion criteria for our review.[74-76]

Neurocognitive testing

Utilised in most studies (93.8%), neurocognitive testing has been considered the cornerstone in concussion diagnosis/management. However, the variety of tests and test components indicate that a uniform approach to neurocognitive test batteries has not been adopted. Although this complicates research, the observed variability of tests and approaches may be reflective of the complexity of neurocognitive changes that occur post-injury. The deficits identified with these measures (e.g., memory & learning, attention and executive function) have been described before,[7 77] underscoring the need for neurocognitive testing to include at least these three domains in the assessment of SRC. There were significant ($p=<0.05$) differences identified in more than half of the athletes in the sub-acute phase when compared to non-concussed controls or individual baselines in the studies that included statistical analysis. The exact aetiologies of these deficits/complaints remain unclear since they probably represent a complex admixture of factors.

While neurocognitive testing can currently be regarded as an important component in the guidance of Return to Play management, especially meaningful after resolution of symptoms,[6] the neurocognitive test findings need to be considered in the context of other symptoms and clinical findings to better judge their relative importance. Collins and colleagues[70] for instance reported on a significant positive correlation of headache and ImPACTs memory and reaction-time composite scores (at 7 days postinjury) in a sample of 110 concussed high school athletes.

The complexity of selecting the right tests, the relationships among tests, and the large number of possible confounding factors (including age, education, sleep habits, drug intake, motivation, language, quality of instructions or frequency of repeated exposure to the test and its relationship to test performance) argues for the use by individuals who are highly skilled in the interpretation of these tests (i.e. neuropsychologists) whenever possible.[50] However, it is important to underscore that neurocognitive tests and measures should not be used in isolation for the purpose of diagnosis or management of SRC.[78]

Balance testing

In those studies meeting inclusion criteria that utilized the BESS, only one study found significant (p>0.05) differences in balance between concussed athletes and a) controls or b) in comparison to baseline results.[48] However, another study identified significant differences in 2/6 BESS test components (tandem gait on different surfaces) when compared to healthy controls 8 days post injury.[20] These results were surprising, since significant differences to preseason scores and matched control subjects on day 1 have been described previously.[79] One explanation might be that athletes included in the review might have been already symptom-free when performing the BESS test. Studies not included in our review but represented in the review on sideline assessment by Echemendia and colleagues[80] indicate the mBESS/BESS appears useful immediately post injury (e.g. 24 hours) in differentiating concussed vs. non-concussed athletes but the ability to differentiate decreases significantly after 3-5 days post-injury. The SOT identified abnormal findings in at least one system (vestibular, visual or somatosensory) in every third athlete. Keeping in mind the high frequency of balance problems, dizziness and blurred vision following head trauma[2 68 81] and the limited amount of normative data,[82] dynamic posturography might be a promising approach for balance screening. However, while useful in the research and clinical centres specializing in concussion management, the expense and bulk of systems such as Neurocom place them beyond the reach of most clinician applications. Consequently, greater emphasis should be placed on developing clinically relevant measurement devices that are easily accessible to clinicians (e.g. accelerometer assisted balance tests, that can be used via smartphones). Additionally, a multifaceted approach to the assessment of balance may also include tests that evaluate dynamic balance and reflect the complexity of tasks required for sport (e.g. tandem gait, gait with head motion, etc.).

Role of baseline testing:

Disagreement exists about the relevance of neurocognitive tests administered at baseline in SRC management due to intra- and inter-individual differences in cognitive domains assessed across the various tests. This is made more complex in children where cognitive development and maturation occur rapidly and may require much more frequent baseline testing.[8] The comparison of post-injury - to baseline results has been proven to be useful when performed two days post-injury by Lau and colleagues.[36] However, since individual baseline testing is labour-intensive and may exceed the financial resources of many organizations, an alternative approach is to make comparisons between the individual's post-injury scores and appropriate normative data where available. To date, studies indicate that the use of normative approaches may be appropriate for a large portion of individuals diagnosed with concussion but may miss some individuals who are not adequately represented in the norming sample.[27 43]

Conversely, it has been demonstrated that comparing "above average" athletes to normative data on a CNP may result in misclassification.[27] Moreover, it is largely accepted in clinical neurocognitive practice that a within person comparison (i.e., using the person as his/her own control) may be an aspirational preference.

The application of the normative comparison method may lead to a more conservative post-injury management.[50]

Limitations

The studies reviewed were diverse, making a comparison of individual studies challenging, thus disallowing any formal meta-analysis. Due to the number of exclusion criteria applied, only published, English-language articles were included, that lead to the risk of publication and language bias. Additionally, only prospective studies were further analysed, that focused on assessment and clinical domains of SRC in the acute phase (up to 14 days post -injury). Due to this time period limitation, relevant studies may have been omitted, where the primary focus was sideline assessment, persistent symptoms, SRC modifiers or follow up (i.e., treatment, rehabilitation or return to play). Moreover, results from studies of non-sports related mild traumatic brain injuries were not examined or evaluated for inclusion in this review. The NOS was deemed to be the most appropriate tool to assess risk of bias as the majority of studies were Case Control or Cohort designs. However in some cases the study designs were cross sectional or case series, this limiting the utility of NOS in some studies. Many of the studies included in this review are vulnerable to measurement bias and selection bias in addition to a lack of control for potential confounding factors, limiting the conclusions that can be drawn. Thus, future research employing high quality designs, including evaluation of multiple systems using standardized, reliable and valid objective measures, will facilitate an improved understanding of the relationship among concussive injury, symptoms and functional alterations following injury.

Conclusion

Symptoms of SRC are heterogeneous and not specific to SRC. The symptoms involve different domains (e.g. cognition, dizziness and balance, emotions, headache and vision). Currently evaluate signs of SRC primarily include only neurocognitive and balance dysfunctions.

Consequently, symptoms should be assessed using a standardized and validated symptom scale (e.g. original version of PCSS) or other empirically based questionnaires. Identified predominant symptoms may need to be assessed in greater detail by validated symptom-specific scales or questionnaires. A review of the current studies yields an imbalance between domains affected by SRC and domains assessed. Domains that have received a great deal of attention include neurocognitive assessment, balance/postural stability, and symptom constellations. Other important but less studied domains within SRC are vestibular, ocular motor, visual, psychological, and cervical symptoms. Further research should include empirical studies, utilizing reliable and valid standardized measures, for the objective assessment of these multiple clinical domains.

Baseline testing for the different domains remains optional, but individual baseline data may assist in the interpretation of post-injury test results in some individuals. Comparison of test results to normative data may lead to a more conservative return to play management. The benefit of baseline test results for other minimally evaluated domains to date including vestibular, ocular-motor, visual, psychological, and cervical functions should be a focus of future study. Early interdisciplinary assessment following a concussion within the first days may facilitate triage for appropriate intervention in a timely fashion.

Tables and Figures

Table 1: Survey on symptoms (according to 22-item Post-Concussion Symptom Scale from SCAT3) and possible aetiology

Figure 1: Flow chart on the selection process of identified articles

Table 2: Data extraction – prospective studies

Table 3: Summary information on included prospective studies

Table 4a: Summary information on symptoms assessed by the Post-Concussion Symptom scale (PCSS, 0-21 (22) items)

Table 4b: Summary information on specific symptoms assessed according to the Post-Concussion Symptom Scale SCAT3 (0-22 items)[i]

Table 5: Survey on studies reporting on neurocognitive testing (n=30)

FIGURES

Table 1: Survey on symptoms (according to 22-item Post Concussion Symptom Scale from SCAT3) and possible aetiology

Signs and symptoms according to PCSS/SCAT3	Possible aetiology		
	Brain (Concussion)	Labyrinth (Vestibular)	Neck (Cervical)
Difficulty concentrating	✓	✓	✓
Difficulty remembering	✓	✗	✗
Feeling slowed down	✓	✓	✗
Confusion	✓	✗	✗
"Don`t feel right"	✓	✓	✓
Fatigue or low energy	✓	✓	✓
Trouble falling asleep	✓	✗	✓
Drowsiness	✓	✗	✗
Feeling like "in a fog"	✓	✓	✓
Balance Problems	✓	✓	✗
Dizziness	✓	✓	✓
Irritability	✓	✓	✓
More emotional	✓	✓	✓
Nervous	✓	✓	✓
Sadness	✓	✓	✓
"Pressure in Head"	✓	✓	✓
Headache	✓	✗	✓
Neck pain	✓	✓	✓
Sensitivity to light	✓	✓	✓
Sensitivity to noise	✓	✓	✗
Nausea or vomiting	✓	✓	✗
Blurred vision	✓	✓	✓

Table 2 Data extraction - prospective studies*

Lead author, study year	Design	Number of participants; age (mean±SD); number of males [%]	Sport; level of play	Comparison group(s)	Base-line	Diagnosis of concussion: who; where; when?	Latency until further exam (FU)	Assessment components	Results	NOS (0-9)	Level of Evi-dence
Broglio et al., 2007[30]	PCS	75; NA; 62 [83]	AF, FB, BB, cheer- leading, others; NA	None	Yes	Physician; NA; immediately	24 hrs	Symptoms [9 items] Neurocognitive [paper-pen incl. HVLT, TMT, SDMT, DST, COWAT, CNP [HCRI], ImPACT (2004-2005), Postural stability [SOT]	When looking at all tests separately, ImPACT and HCRI were most sensitive for concussion (79.2% and 78.6% respectively). When all tests were combined, sensitivity exceeded 90%.	4	3
Collie et al., 2006[57]	PCS	61,(25 symptomatic / 36 asymptomatic); 22.3±3.6 / 23.3±3.9; 61 [100]	ARF; professional	Non concussed athletes same sports (n=84)	Yes	Club medical staff; NA; immediately	11 d	Symptoms (14 items) CNP [CogSport], paper pen (DSST, TMT)	Compared to asymptomatic and control group, the performance of the concussed symptomatic group declined after injury on computerised tests for simple, choice, and complex RT. On paper and pen tests the symptomatic group displayed no change after reassessment, whereas large improvements were seen in the other two groups.	6	3
Collins et al,. 2003[52]	Case Control	78; 16.8±2.4; 69 [89]	AF, FB, hockey, BB, lacrosse, baseball; high school, college	Non injured athletes just to estimate practice effects; comparison of symptomatic vs asymptomatic	Yes	Sports medicine practitioners; on field; mmediately	within 5 d, mean 1.7 d	Symptoms [PCSS ImPACT] CNP [ImPACT],	Compared to the asymptomatic group, the symptomatic group was over 10 times more likely (p<0.001) to exhibit retrograde amnesia and over 4 times more likely (p<0.013) to have exhibit posttraumatic amnesia. However, there was no difference between the groups in terms of on-field loss of consciousness.	7	4
Covassin et al., 2010[32]	Case Series	72; 15.8 ± 1.3; 58 [81]	baseball, BB, cheerleading, AF, gymnastics, IH, FB, softball, VB, wrestling, others; high school	None	Yes	Certified athletic trainers, team physicians; sideline; immediately	2, 7, 14, 21, 30 d	Symptoms [ImPACT] CNP [ImPACT]	Compared to baseline, concussed athletes scored worse on reaction time (p=0.000), verbal memory (p=0.012), motor processing speed (p=0.000) and total symptoms (p=0.000). Values returned to baseline level within 7-21 days.	5	4
Echemendia et al., 2001[7]	PCS	29; NA; NA	AF, IH, FB, BB; college	Non concussed athletes (n=20), same sport	Yes	Athletic trainer, neuropsychologist, physician; sideline; immediately	2 & 48 hrs, 1 wk, 1 mth	Symptoms [PCSS] Neurocognitive [HVLT, SDMT, SCWT, TMT, VCPT,,DST, PSCT, COWAT, SCWT]	Compared to controls, concussed athletes scored worse on neuropsychological tests 2 hrs (p=0.000-0.020) and 48 hrs (p=0.000-0.038) after injury. However, a significantly greater number of symptoms was found 2 hrs after injury only (p=0.044).	5	4
Echlin et al., 2012[33]	PCS	11; NA; 5 [46]	IH; college	None	Yes	Physician, self-reported; sideline; immediately	72 hrs, 2 wks, 2 mth, post-season	Symptoms [SCAT2] CNP [ImPACT, SCAT2] Imaging [3 T-MRI (DTI, MRS, SWI)] Balance [SCAT2]	Compared to baseline, ImPACT scores were significantly declined 72 hrs after injury in concussed athletes (p<0.05). The number of symptoms increased significantly immediately after injury and returned to baseline by the time of post-season evaluation.	5	4
Eckner et al,. 2011[34]	Case Series	9; 20.6±1.0; 8 [89]	AF, FB, wrestling; university	None	Yes	Physician; NA; NA	72 hrs	Symptoms [SCAT] CNP [CogSport, RT]	Compared to baseline, clinical RT was prolonged in 8 out of 9 concussed athletes while computerized RT was prolonged in 5 out of 9 concussed athletes. Indicating clinical RT might be more sensitive for detecting concussion.	4	4
Fazio et al., 2007[19]	CrS	122 (78 symptomatic and 44 asymptomatic); 16.7; 99 [81]	AF, FB, BB, wrestling, swimming, track, others; high school, college	Non concussed athletes different sports (n=70)	Yes	Certified athletic trainers or team physicians; sideline; immediately	within 7 d, mean 45.1 hrs	Symptoms [ImPACT] CNP [ImPACT]	Compared to controls and asymptomatic athletes, symptomatic athletes scored worse on all four composite scores of the ImPACT (in all cases p<0.00).	4	4
Fuller et al., 2015[35])	Diagnostic Accuracy	65; NA; 65 [100]	Rugby; elite	None	No	Physician; sideline (suspected), confirmed in clinical setting; immediately	within 48 hrs postgame	PSCA Symptoms [SCAT2] CNP [CogSport, ImPACT, SCAT2]	The PSCA tool demonstrated a sensitivity of 84.6 %(95% CI 73.5% to 92.4%) and a specificity of 74% (95% CI 64.3% to 82.3%) for identification of concussion.	5	2
Furman et al., 2013[20]	CrS	10,[symptom duration <2wk in total 43 concussed]; 16±1.5; 9 [90]	NA; high school	Non injured participants (n=27) Symptom duration >2 wk (n=33)	Yes	Physician; Clinical setting; Within 14 d postinjury	Acute 8 d ± 3 d	Postural stability [BAM, BESS]	Compared to controls, concussed adolescents scored worse on the BESS (p<0.04), but no difference between the groups was observed on the BAM. A total BESS score of ≥21 errors identified athletes in the acute concussion group at 60% sensitivity and 82% specificity with 95% confidence interval.	2	3
Gardner et al., 2012[53]	CrS	46; 24.2±4.2; 46 [100]	rugby; amateur	Non concussed athletes (n=41) same sports	No	Team medical staff; NA; NA	72 hrs (mean 46.4 hrs)	Symptoms [ImPACT] CNP [CogSport, ImPACT]	When looking at all tests separately, the ImPACT post-concussion symptoms total was most accurate in classifying concussed athletes (accuracy 88.5%, Wald statistic p=0.006).	6	3
Graves et al., 2016[40] (NA)	PCS	15; 18.9±0.9; 15 [100]	AF; college, division 1	Non concussed athletes different sports, currently not competing (n=15)	Yes	Athletic trainer and team physician; sideline; immediately	24 hrs, after injury, 14 d after asymptomatic	Symptoms [NA] Postural stability [SOT, BESS]	Compared to baseline and control group, the concussed athletes had a significant decline in SOT score after injury (p=0.037 and p=0.025 respectively).	6	4
Houston et al., 2016[41]	Case Series	122; 15.8±1.1; 102 [84]	AF, FB, others; high school	None	Yes	Athletic trainers; sideline; immediately	3 d, 10 d	Symptoms [SCAT2] HRQoL Questionnaire [PedsQL, PedsQL-MFS, HIT-6} Neurocognitive [SAC] Postural Stability [BESS]	When comparing symptoms to HRQoL questionnaires and neuropsychological on how much variance in time lost they can explain, HRQoL questionnaires are able to explain17.9-15.2% while symptoms explain 7.1% and neuropsychological explains 12.0% of this variance.	5	4
Iverson et al., 2004[42]	CrS	110 (91 no fogginess, 19 with fogginess); 15.8±1.2; 93 [85]	AF, BB, FB, Hockey, lacrosse, softball,, track, volleyball, wrestling;high school	None	Yes	Certified athletic trainers or physicians; sideline; immediately	5-10 d post injury (mean 6.8 d)	Symptoms [ImPACT] CNP [ImPACT]	Compared to concussed athletes without fogginess, concussed athletes had a significant higher total symptom score (p<0.0001), slower reaction time (p<0.0002), reduced memory performance (p<0.01), and slower processing speed (p<0.004).	4	4
Lau et al., 2009[4]	PCS	108 (47 simple concussion, 61 complex concussion); 16.0±1.2; 108 [100]	AF; high school	None	Yes	Athletic trainers or physicians; sideline; immediately	complex 0-12d (mean 2.4 d), simple 0-5d (mean 2.0 d)	Symptoms [ImPACT] CNP [ImPACT]	Compared to athletes with simple concussion, athletes with complex concussion scored significantly worse on visual memory (p=0.016), processing speed (0.007) and total symptom score (p=0.002). However, no difference was found in reaction time (p=0.088) and verbal memory performance (p=0.796). When comparing concussed athletes who experienced loss of consciousness (n=20) with the rest of the concussed athletes, no differences were found with regard to either neuropsychological performance (p=0.217) or symptoms (p=0.610).	7	4
Lau et al., 2011[36]	PCS	108,(58 short recovery, 50 protracted recovery); 16.0±1.2; 108 [100]	AF; high school	None	Yes	Athletic trainers and/or team physicians; sideline; immediately	Short recovery 0-5 d (mean 1.5d), protracted 0-12d (mean 2.6d)	Symptoms [ImPACT] CNP [ImPACT]	Compared to using total symptom score alone to predict concussion, combining symptoms with CNP increases sensitivity with 24.41% and specificity with 1.05%, resulting in a total sensitivity of 65.22% and specificity of 80.36% with CI of 80%.	5	4
Lau et al., 2012[56]	PCS	108,(58 short recovery, 50 protracted recovery); 16.0±1.2; 108 [100]	AF; high school	None	Yes	Athletic trainers or physicians; sideline; immediately	Short recovery 0-5 d (mean 1.5d), protracted 0-12d (mean 2.6d)	Symptoms [ImPACT] CNP [ImPACT]	Compared to the short recovery group, the protracted recovery group reported significantly more often migraine (p=0.01) and cognitive symptoms (p=0.04). They also performed worse in visual memory (p=0.01) and processing speed (p=0.02).	8	4
Louey et al., 2014[43]	PCS	29; 22.3± 2.90; 29 [100]	ARF; Rugby, professional, college	Non concussed athletes (n=235)	Yes	Team doctor, sideline; immediately	mean 32.1 ±4.1 hrs	Symptoms [Collie, A 2006] CNP [CogSport]	Compared to the normative method, the baseline method showed higher sensitivity (96.6 vs. 69.0, 95% CI); specificity did not differ (86.9 vs. 91.5, 95% CI).	6	4
Lovell et al.	Case	43; 15.6; 35 [81]	AF, FB, BB, IH, lacrosse,	None	Yes	Trained athletic trainers	36 hrs (mean1.4 d),	CNP [ImPACT] Symptoms	Compared to baseline, concussed athletes showed a decline in memory (p<0.003) and an	4	4

Lead author, study year	Design	Number of participants; age (mean±SD); number of males [%]	Sport; level of play	Comparison group(s)	Base-line	Diagnosis of concussion: who; where; when?	Latency until further exam (FU)	Assessment components	Results	NOS (0-9)	Level of Evi-dence
2004[21]	Series		baseball, softball; high school			physicians; sideline; immediately	6 d	[ImPACT]	increase in self-reported symptoms (p<0.00001) after injury.		
Lovell et al., 2006[44]	CrS+Case Series	260; 16.5±2.0; 217 [84]	Athletes; high school, college	None	Yes	Certified athletic trainer or team physician; sideline; immediately	within 5 d (mean 48 hrs), 52 athletes 3 times (mean 1.4 d ± 0.7, 2= 5.6 d ± 1.3, 3= 11.7 d ± 4.2).	Symptoms [PCSS]	Compared to men, women tended to report more symptoms. The most frequently endorsed symptoms were: headache and difficulty concentrating. PCSS showed a good internal consistency for concussed athletes (r=0.93).	5	4
Maddocks et al. 1995[45]	PCS	28; NA; 28 [100]	ARF; college, professional	Non concussed athletes same sports (n=28) with injury other than concussion	No	Medical practitioner; dressing room; immediately	Within 2 hrs	Symptoms [7 items] Neurocognitive (orientation, memory)	Compared to controls, the concussed athletes reported more frequently headache (93% vs 18%) and blurred vision (75% vs 0%) and performed significantly worse on short time memory items (0.001<p<0.004); no group difference with respect to orientation (0.06<p<1.00).	6	4
Maddocks et al., 1996[22]	CrS	10; NA; 10 [100]	ARF; professional	Non concussed athletes same sports (n=10)	Yes	Club medical practitioner; NA; NA	5 d	Neurocognitive [PASAT, DSST, FCRT (divided in DT and MT)]	Compared to controls, concussed athletes performed worse on DSST (p=0.04) and DT (p=0.01) after injury; no significant differences for MT (p=0.11) or PASAT (p=0.71).	4	4
Makdissi et al., 2001[46]	PCS	6; 20.5± 3.1; 9 [100]	ARF; elite professional, semi-professional, amateur	Non concussed athletes same sports (n=7)	Yes	Club medical practitioner; NA; NA	2 d	Symptoms [7 items] CNP [CogSport (SRT)], Neurocognitive [DSST, TMT]	Compared to baseline, concussed athletes showed an increase in variability in SRT (p=0.01); no differences in DSST (p=0.72) ,TMT (p=0.21) or RT (p=0.053) scores for the concussed or control group.	6	4
McClincy et al., 2006[23]	Case Series	104; 16.1±2.2; 91 [88]	AF, FB, BB, wrestling, IH, FH, others; high school, college	None	Yes	NA; NA; NA	2 d (2.42± 3.1) d), 1 wk (7.6±4.5 d), 2 wks (14.4±7.3 d)	Symptoms [ImPACT- 21 items] CNP [ImPACT]	Compared to baseline, concussed athletes scored significantly worse on all ImPACT composite scores including total symptom score 2 d after injury (p<0.0001 in all conditions). 7d after injury significant difference for verbal memory (p<0.0001), visual memory (p<0.01), RT (p<0.0002) and total symptom score (p<0.0001); after 14d significant difference only found for verbal memory (p<0.0003).	5	4
McCrea et al., 2002[47]	PCS	91; 17.5± 2.10; 91 [100]	AF; high school, college	None	Yes	Certified athletic trainer; sideline; immediately	15 min, 48 hrs, 90 d	Neurocognitive [SAC]	Compared to baseline, SAC scores were significantly lower in concussed athletes 15 min after injury (0.035<p<0.008). All groups returned to baseline level within 48 hrs.	6	4
McCrea et al., 2003[58]	PCS	94; 20.0±1.4; 94 [100]	AF; college division I, II, III	Non concussed athletes same team (n=56)	Yes	Team physicians or certified athletic trainers; sideline; immediately	3 hrs, 1, 2, 3, 5, 7, 90 d	Symptoms [GSC, 17 items] Neurocognitive [SAC, HVLT (Immediate, Delayed, Recognition, TMT Part B, SDMT, SCWT, COWAT], Postural stability [BESS]	Compared to controls, concussed athletes scored higher on GSC (mean 20.93), lower on cognitive impairment (mean, 2.94) and worse on balance (mean 5.81). On average symptoms resolved in 7 d.	8	3
Pearce et al., 2015[25]	PCS	8; 25.1±4.5; 8 [100]	ARF; amateur	Non concussed athletes same sports (n=15)	No	Sports trainer, or self – observation; sideline; immediately	48, 96 hrs,, 10 d	Neurocognitive [O'Connor Finger Dexterity test, Visuomotor reaction time, VMRT (RT+MT)], CNP [CANTAB (PAL, IED)], TMS [MEP]	Compared to controls, concussed athletes showed increase in RT (p=0.02) and MT (p=0.01) 48 hrs after injury, decrease in attentional performance 48 and 96 hrs after injury (p<0.01 for both) and an increase in cortical inhibition 48 (p=0.04) and 96 hrs (p=0.02) after injury, which correlated significantly with RT (r=0.48, p<0.01), MT (r=0.42, p=0.02) and attentional performance (r=0.44, p=0.01).	4	4
Pearce et al,. 2015[15]	CrS	78; 14.3±2.8; 45 [35]	NA; high school	None	No	NA; NA; NA	5.8, 5.6 d	Symptoms [ImPACT] CNP [ImPACT] NPC	Athletes with NPC impairment performed worse on verbal memory (p=0.02), visual motor speed (p= 0.02), and RT (P =0.001) and had a greater total symptom score (p=0.02)	3	4
Pellman et al., 2004[83]	PCS	95; 25.4 (NFL, including all), College 20.4); 95 [100]	AF; college, professional	None	Yes	Neuropsychologist; NA; NA	1.4 d	Symptoms [NA] Neurocognitive [HVLT, BVMT-R, TMT, SDMT, COWF, DST]	The concussion group did not display significant neuropsychological dysfunction relative to baseline scores (except for TMT, Part A (p=0.03), DST (p= 0.001), SDMT (p= 0.006).	6	3
Putukian et al., 2015[48]	Diagnostic Accuracy	32; 20.8±1.0; 27 [84]	AF, rugby, IH, water polo, (sprint) FB, BB, lacrosse, FH, wrestling; University, division I	Non concussed contact sport athletes (n=23)	Yes	Team physician; NA; NA	12.5 hrs	Symptoms [SCAT-2] Questionnaire [GAD-7, PHQ-9] Neurocognitive [SCAT2] Balance [SCAT2]	Compared with baseline, the total SCAT2 score and the composite scores of symptoms (severity) and balance were significantly impaired; compared with controls, all SCAT2 subcomponents were significantly impaired (p< 0.01); compared with baseline, a 3.5-point drop in SCAT2 score had 96% sensitivity/ 81% specificity in detecting concussion.	6	3
Schmidt et al., 2012[84]	PCS	258; male: 18.8±1.6 female: 18.5±1.1; 182 [71	NA; college	None	Yes (n=175)	Medical staff; NA; NA	Within 10 d (mean 2.7 d)	Symptoms [GSC, 15 items] CNP [ANAM] Postural stability [SOT]	The baseline method identified 2.6 times more impairments than the normative method for the Simple Reaction Time Test 1 (p=0.043). The normative method identified 7.6 times more impairments than the baseline method for Mathematical Processing (P G 0.001); no disagreements for postural control or symptom severity.	5	4
Seidman et al., 2015[16]	PCS	9; 15.6±1.0; 9 [100]	AF	athletes same sports without concussion	Yes	Certified team staff; sideline immediately	30 min	Symptoms [ImPACT] CNP [ImPACT, SCAT3], Postural stability [SCAT3], Visual/ocular motor [KD]	In all concussed players, cumulative read times for the KD test were significantly increased (p= 0.001)	6	4
Van Kampen et al., 2006[29]	PCS	122; 16,6; 100 [82]	AF, FB, BB, IH, wrestling, lacrosse; high school, college	None concussed athletes different sports (swimmer, FB, track, wrestling, lacrosse) (n=70)	Yes	Certified athletic trainer or physician; sideline; immediately	48 hrs	Symptoms [ImPACT] CNP [ImPACT]	Compared with baseline a significant increase in symptoms was reported in 64% and poorer neurocognitive test results in 83% of the concussed sample. The addition of neurocognitive testing resulted in a net increase in sensitivity of 19%.	5	4

* See Supplementary Table 1 for detailed information (incl. the retrospective studies)

Abbreviations: Study designs: CrS= Cross-sectional Study, PCS= Prospective Cohort Study, *CrS= Cross-Sectional Study using retrospectively collected data, RCS= Retrospective Cohort Study; **Tests**: ANAM= Automated Neuropsychological Assessment Metrics, BAM= Health`s Balance Accelerometer Measure, BESS= Balance Error Scoring System, BVMT-R= Brief Visual Spatial Memory Test, CNP= Computerized Neuropsychological Test, CANTAB= Cambridge Neuropsychological Test Automated Battery, CogSport = CogSport Ltd, Melbourne, Australia, COWAT= Controlled Oral Word Association Test, COWF= Controlled Oral Word Fluency, DS= Digit Spam, DSST= Digit Symbol Substitution Test, DST=Digit Spam Test, DT= Decision Time, DTI= Diffusion Tensor Imaging, FCRT= Four Choice Reaction Time, GAD= Generalize Anxiety Disorder-7 item, GCS= Glasgow Coma Scale, GSC= Graded Symptom Checklist, HCRI= HeadMinder Concussion Resolution Index, HIT-6= Headache Impact Test 6, HRQoL= Health Related Quality of Life, HVLT= Hopkins Verbal Learning Test, IED= Intra-Extra Dimensional Set Shift, ImPACT= Immediate Post Concussion Assessment and Cognitive Testing, KD= King-Devick Test, LOC= Loss of Consciousness, MEP=Motor Evoked Potential, MFS= Multidimensional Fatigue Scale, MRS= Magnetic Resonance Spectroscopy MT= Movement Time, NPC= Near Point Convergence, PAL= Paired-Associative Learning, PASAT= Paced Auditory Serial Addition Test, PCSS= Post Concussion Symptom Scale, PedsQL= Paediatric Quality of Life inventory, PHQ-9= Patient Health Questionnaire-9, PSCA= Pitch Side Concussion Assessment, PSCT= Penn State Cancellation Test, RT= Reaction Time, SAC= Standardized Assessment of Concussion, SCAT= Sport Concussion Assessment Tool, SCAT2= Sport Concussion Assessment Tool 2nd edition, SCAT3= Sport Concussion Assessment Tool 3rd edition, SCWT= Stroop Colour-Word Test, SDMT= Symbol Digit Modalities Test, SOT= NeuroCom Sensory Organization Test, SRT= Simple Reaction Time, SWI= Susceptibility Weighted Imaging, T-MRI= Tesla magnetic resonance imaging, TMS= Transcranial Magnetic Stimulation, TMT= Trail Making Test, VCPT= Vigil Continuous Performance Test, VMRT= Visuomotor Reaction Time **Type of sports:** AF= American Football, ARF= Australian Rules Football, BB= Basketball, FB= Football/ (soccer), FH= Field Hockey, IH= Ice Hockey, VB= Volleyball, others = mixed**; Others**: d= day; FU= Follow Up, hrs= hours, incl.= including, min= minutes, mth= month, NA= Not available, SD= Standard Deviation, wk= week

Table 3: Summary information on included prospective studies

	Number of studies, n [%]	Total number of athletes, n [%]	Number of athletes in studies (n=8) with exclusively American Football players, n [%] 4 16 36 40 47 56 58 59	Number of athletes in studies including exclusively males, n [%] 4 16 22 25 35 36 40 43 45-47 53 56-59
Total	33 4 7 15 16 19-23 25 29 30 32-36 40-48 50 52 53 56-59	2416	628 [26.0]	881 [36.5]
Mean age in years	27 4 15 16 19-21 23 25 29 32 34 36 40-44 46-48 50 52 53 56-59	17.4*±4.6	17.0±1.4	18.4±2.2
Sports				
American football	19 [57.6] 4 7 16 19 21 23 29 30 34 36 40-42 47 48 52 56 58 59	1191 [49.3]		628 [71.3]
Rugby	3 [9.1] 35 48 53	119 [4.9]		111 [12.6]
Australian Rules Football	6 [18.2] 22 25 43 45 46 57	142 [5.9]		142 [16.1]
Football (Soccer)	11 [33.3] 7 19 21 23 29 30 34 41 42 48 52	85 [3.5]		NA
Ice Hockey	4 [12.1] 7 23 33 48	29 [1.2]		NA
Basketball	8 [24.2] 7 19 21 29 30 42 48 52	53 [2.2]		NA
Other sports	14 [42.4] 15 19-21 23 29 30 32 41 42 44 48 50 52	797 [33.0]		NA
Level of play				
High-school /college	19 [57.6] 4 7 15 19-21 23 29 32 36 40-44 47 52 56 58	1961 [81.2]	524 [83.4]	553 [62.8]
University	3 [9.1] 33 34 48	52 [2.2]		
Amateur	3 [9.1] 25 46 53	55 [2.3]		55 [6.2]
Professional	6 [18.2] 22 35 45 46 57 59	264 [10.9]	95 [15.1]	264 [30.0]
Not specified	2 [6.1] 16 30	84 [3.5]	9 [1.4]	9 [1.0]
Who made the diagnosis of SRC?				
Athletic trainer	5 [15.2] 4 25 30 36 56 58	426 [17,6]	418 [66.6]	426 [48.4]
Certified trainer	7 [21.2] 19 29 32 41 42 44 47	899 [37.2]	91 [14.5]	91 [10.3]
Team medical staff	9 [27.3] 7 16 22 45 46 50 52 53 57	525 [21.7]	9 [1.4]	160 [18.2]
Team physician	5 [15.2]	184 [7.6]	15 [2.4]	109 [12.4]

	21 35 40 43 48			
Physician	4 [12.1] 20 30 33 34	105 [4.3]		
Neuropsychologist	1 [3.0] 59	95 [3.9]	95 [15.1]	95 [10.8]
Not specified	2 [6.1] 15 23	182 [7.5]		
Where was the diagnosis made?				
Sideline	19 [57.6] 4 7 16 19 21 25 29 32 33 36 40-44 47 52 56 58	1539 [63.7]	533 [84.9]	570 [64.7]
Clinical setting	2 [6.1] 20 35	75 [3.1]		65 [7.4]
Not specified	12 [36.4] 15 16 22 23 30 34 45 46 48 50 53 57 59	802 [33.2]	95 [15.1]	246 [27.9]
When took the "first" evaluation place?				
Immediately	19 [57.6] 4 7 21 25 30 32-36 40-43 47 52 56-58	1236 [51.2]	524 [83.4]	687 [78.0]
< 24 hrs	1 [3.0] 16	9 [0.4]	9 [1.4]	9 [1.0]
>24 to 48 hrs	2 [6.1] 19 29	244 [10.1]		
> 48 hrs	4 [12.1] 20 44 46 53	322 [13.3]		52 [5.9]
Not specified (declared as FU exam < 24 hrs 24 - 48 hrs > 48 hrs	7 [21.2] 1 [48] 3 [22 23 59] 3 [15 45 50]	605 [25.0]	95 [15.1]	133[15.1]
Baseline Tests				
Neurocognitive testing	24 [72.7] 4 7 16 19 21-23 29 30 32-34 36 41-43 46-48 50 52 56-59	1896 [78.5]	613 [97.6]	719 [81.6]
Balance	8 [24.2] 20 30 33 40 41 48 50 58	617 [25.5]	118 [17.4]	109 [12.4]
Ocular motor function	2 [6.1] 15 16	87 [3.6]	9 [1.4]	9 [1.0]

[*] Mean age was calculated based on information on mean age and SD and in relation to total number of athletes included in each study (all: n=23 studies,, AF: n=7 studies, male: n=12 studies; 10 studies did not provide full information ;

Table 4a: Summary information on symptoms assessed by the Post-Concussion Symptom scale (PCSS, 0-22 items

Parameter	< 24 hrs	24 - 48 hrs	> 48 hrs	Total
Number of studies	2 [7 48]	6 [23 29 32 44 52 53]	6 [4 15 33 36 41 42]	14*
Number of concussed athletes	61	474	537	1072
Range time between injury and assessment	2-12.5	33.6-48	53-163.2	
Range number of symptoms post- injury Range number of symptoms baseline	9 2.6	20 5	8.3 3.9	
Range total symptom severity score post injury Range total symptom severity score baseline	8.5-19.4 1.5-2.5	14.4-45.6 4.2-10.7	14.7-35,9 11.0	
Number of studies reporting on symptoms of athletes (at first visit)	0†	2[44 53]	1[42‡]	3

* In five additional studies PCSS was used, but no information on outcome was given.[16 19 21 35 56]
† In one additional study no information on number of athletes was given, in another study information.[7]
‡ In one additional study no information on number of athletes was given.[4]

4b: Summary information on specific symptoms assessed according to the Post-Concussion Symptom Scale SCAT3 (0-22 items) [*]

Parameter	Lovell et al. 2006[44] Number of athletes[†] [%]	Gardner et al. 2012[53] Number of athletes [%]	Total Number of athletes [%]
Total	52	46	98
Alertness/Attention			
- *Difficulty remembering*	36 [69.2]	11 [23.9]	47 [48.0]
- *Difficulty concentrating*	43 [82.7]	17 [37.0]	60 [61.2]
- *Feeling slowed down*	41 [78.8]	17 [37.0]	58 [59.2]
Consciousness/Awareness			
- *Confusion*			
- *Fatigue or low energy*	40 [76.9]	22 [47.8]	62 [63.3]
- *Drowsiness*	38 [73.1]	20 [43.5]	58 [59.2]
- *Trouble falling asleep*	23 [44.2]	9 [19.6]	32 [32.7]
- *„Don't feel right“*			
Dizziness & Balance			
- *Dizziness*	41 [78.8]	17 [37.0]	58 [59.2]
- *Feeling like "in a fog"*	39 [75.0]	14 [30.4]	53 [54.1]
- *Balance Problems*	29 [55.8]	11 [23.9]	40 [40.8]
Emotion			
- *Irritability*	20 [38.4]	9 [19.6]	29 [29.6]
- *Nervous*	16 [30.8]	2 [4.3]	18 [18.4]
- *More emotional*	10 [19.2]	5 [10.9]	15 [15.3]
- *Sadness*	10 [19.2]	3 [6.5]	13 [13.3]
Headache/Migraine			
- *Headache*	46 [88.5]	42 [91.3]	88 [89.8]
- *Nausea or vomiting*	46 [88.5]	8 [17.4]	54 [55.1]
- *Sensitivity to light*	30 [57.7]	9 [19.6]	39 [39.8]
- *Sensitivity to noise*	NA	4 [8.7]	4 [4.1]
- *"Pressure in head"*	NA	NA	
- *Neck pain*	NA	NA	
Vision			
- *Blurred vision*	17 [32.7]	8 [17.4]	25 [25.5]

[*] Symptoms were transferred in the symptom list of SCAT3.
[†] Athletes could report one or more symptoms.

Table 5: Survey on studies reporting on neurocognitive testing (n=30)

Domain	Executive function	Motor skills	Memory and learning	Visual spacial skills	Language	Attention
Number of studies	29 4 7 15 16 19 21-23 25 29 30 32-36 41-43 46-48 50 52 53 56-59	24 4 15 16 19 21-23 25 29 30 32 33 35 36 41 42 46-48 52 53 56-58	30 4 7 15 16 19 21-23 25 29 30 32-36 41-43 45-47 50 52 53 56-59	3 7 25 59	4 7 30 58 59	26 4 7 15 16 19 21-23 25 29 30 32-36 42 43 46 50 52 53 56-59
Number of test categories	8	6	8	3	2	13
Post-injury test categories	ANAM, CANTAB, CogSport, ImPACT, DSST, SAC, SCWT, TMT	CANTAB, ImPACT, DSST, HCRI, SAC, VMRT	ANAM, CANTAB CogSport, ImPACT, DST, DSST, HVLT, SAC	BVMT-R, VMRT, PSCT	COWAT COWF	ANAM, CANTAB, CogSport, ImPACT, DST, FCRT, HCRI, PASAT, RT, SDMT, SRT, TMT, VCPT
Number of studies with baseline tests*, n [%]	25 [86.2] 4 7 16 19 21-23 29 30 32-34 36 41-43 46-48 50 52 56-59	20 [83.3] 4 16 19 21-23 29 30 32 33 36 41 42 46-48 52 56-58	25 [83.3] 4 7 16 19 21-23 29 30 32-34 36 41-43 46-48 50 52 56-59	2 [66.7] 7 59	4 [100] 7 30 58 59	22 [84.6] 4 7 16 19 21-23 29 30 32-34 36 42 43 46 50 52 56-59
Differences, when compared concussed to baseline*, n [%] • Significant (p<0.05) • Not significant (p>0.05) • Not specified	5 [20.0] 5 [20.0] 15 [60.0]	2 [10.0] 1 [5.0] 17 [85.0]	8 [32.0] 2 [8.0] 16 [64.0]	0 1 [50.0] 1 [50.0]	0 1 [25.0] 3 [75.0]	8 [36.4] 3 [13.6] 11 [50.0]
Number of studies with control group(s), n [%]	11 [37.9] 7 19 22 25 29 43 46 53 57 58	9 [37.5] 19 22 25 29 46 53 57 58 48	12 [40.0] 7 19 22 25 29 45 46 53 57 58 43 48	2 [66.7] 7 25	2 [50.0] 7 58	10 [38.5] 7 19 22 25 29 43 46 53 57 58
Differences, when compared concussed to controls, n [%]* • Significant (p<0.05) • Not significant (p>0.05) • Not specified	6 [54.5] 0 5 [45.5]	3 [33.3] 0 6 [66.7]	7 [58.3] 1 [8.3] 5 [41.7]	0 0 2 [100.0]	0 0 2 [100.0]	5 [50.0] 2 [20.0] 4 [40.0]
Looking at specific features†, n	6 4 15 19 36 42 57	6 4 15 19 36 42 57	5 4 15 19 36 42	0	0	6 4 15 19 36 42 57

Abbreviations:

ANAM= Automated Neuropsychological Assessment Metrics, BVMT-R= Brief Visual Spatial Memory Test, CANTAB= Cambridge Neuropsychological Test Automated Battery, CogSport= CogSport Ltd, Melbourne, Australia, COWAT= Controlled Oral Word Association Test, COWF= Controlled Oral Word Fluency,DSST= Digit Symbol Substitution Test, DST= Digit Span Test, FCRT= Four Choice Reaction Time, HCRI= HeadMinder Concussion Resolution Index, HVLT= Hopkins Verbal Learning Test,

ImPACT= Immediate Post Concussion Assessment and Cognitive Testing, PASAT= Paced Auditory Serial Addition Test, PSCT= Penn State Cancellation Test, RT= Reaction Time, SAC= Standardized Assessment of Concussion, SCWT= Stroop Colour-Word Test, SDMT= Symbol Digit Modalities Test, SRT= Simple Reaction Time, TMT= Trail Making Test, VCPT= Vigil Continuous Performance Test, VMRT= Visuomotor Reaction Time

* Due to different results in different test categories the total number of studies reporting on differences can be higher than total number of studies with baseline testing
† "Fogginess",[42] "Simple" vs "complex" concussion,[4] "Near point convergence",[15] "Symptomatic vs asymptomatic",[19 57] "Long vs short recovery".[36]

Required statements

Acknowledgements: The authors thank Rosa Vissher for support in study identification, data extraction and analysis. The authors thank Dzmitry Katsiuba for support in data analysis.

Scientific contributions:

Dr. Feddermann conceived the study, designed the search strategy, selected suitable articles, extracted and analysed the data, drafted the manuscript and approved the final version of the manuscript.
Prof. Dvorak reviewed the initial search strategy, critically reviewed the manuscript and approved the final version.
Dr. Schneider reviewed the initial search strategy, critically reviewed the manuscript and approved the final version.
Dr. Turner reviewed the initial search strategy, critically reviewed the manuscript and approved the final version.
Dr. Echemendia reviewed the initial search strategy, critically reviewed the manuscript and approved the final version of the manuscript.
Dr. Hayden designed and reviewed search strategy, performed study search and approved the final version of the manuscript.
Dr. Solomon reviewed the initial search strategy, critically reviewed the manuscript and approved the final version.
Prof. Straumann reviewed the initial search strategy, critically reviewed the manuscript and approved the final version.
Dr. Tarnutzer selected suitable articles, supported data analysis, supported in drafting of the manuscript and approved the final version of the manuscript.

Conflict of interest statements

Dr. Feddermann reports no conflict of interest.
Prof. Dvorak reports no conflict of interest.
Dr. Schneider has received speaking honoraria for presentations at scientific meetings. She is a physiotherapy consultant at Evidence Sport and Spinal Therapy and for many athletic teams.
Dr. Echemendia is co-chair of the NHL/NHLPA Concussion Subcommittee, chair of the MLS Concussion Committee, and a neuropsychological consultant to Princeton University and the US Soccer Federation. He receives financial compensation for each of these activities. He is engaged in the practice of clinical neuropsychology and occasionally serves as an expert in medico-legal cases involving TBI and SRC. He has received speaking honoraria for presentations at scientific meetings.
Dr. Turner reports no conflict of interest.
Dr. Solomon is a full time employee of the Vanderbilt University Medical Center. He is a consulting neuropsychologist for the NHL Nashville Predators, NFL Tennessee Titans, and

several collegiate athletic teams, with all fees paid to institution. He is also a member of the ImPACT Scientific Advisory Board, and receives expense reimbursements for attendance at board meetings. He has received speaking honoraria for presentations at scientific meetings.

Prof. Straumann reports no conflict of interest.

Dr. Tarnutzer reports no conflict of interest.

References:

1. McCrory P, Meeuwisse W, Aubry M, et al. Consensus Statement on Concussion in Sport-the 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *Clin J Sport Med* 2013;23(2):89-117 29p. doi: 10.1097/JSM.0b013e31828b67cf
2. Mucha A, Collins MW, Elbin RJ, et al. A Brief Vestibular/Ocular Motor Screening (VOMS) assessment to evaluate concussions: preliminary findings. *Am J Sports Med* 2014;42(10):2479-86. doi: 10.1177/0363546514543775 [published Online First: 2014/08/12]
3. Giza CC, Kutcher JS, Ashwal S, et al. Summary of evidence-based guideline update: Evaluation and management of concussion in sports. *Neurology* 2013;80(24):2250-57.
4. Lau B, Lovell MR, Collins MW, et al. Neurocognitive and symptom predictors of recovery in high school athletes. *Clin J Sport Med* 2009;19(3):216-21.
5. Kontos AP, Elbin RJ, Schatz P, et al. A revised factor structure for the post-concussion symptom scale: baseline and postconcussion factors. *Am J Sports Med* 2012;40(10):2375-84.
6. Echemendia RJ, Bruce JM, Meeuwisse W, et al. Long-term reliability of ImPACT in professional ice hockey. *The Clinical neuropsychologist* 2016;30(2):328-37.
7. Echemendia RJ, Putukian M, Mackin RS, et al. Neuropsychological test performance prior to and following sports-related mild traumatic brain injury. *Clin J Sport Med* 2001;11(1):23-31.
8. Echemendia RJ, Iverson GL, McCrea M, et al. Advances in neuropsychological assessment of sport-related concussion. *Br J Sports Med* 2013;47(5):294-8. doi: 10.1136/bjsports-2013-092186 [published Online First: 2013/03/13]
9. Makdissi M, Cantu RC, Johnston KM, et al. The difficult concussion patient: what is the best approach to investigation and management of persistent (>10 days) postconcussive symptoms? *Br J Sports Med* 2013;47(5):308-13.
10. Moher D, Liberati A, Tetzlaff J, et al. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *J Clin Epidemiol* 2009;62(10):1006-12. doi: 10.1016/j.jclinepi.2009.06.005
11. Wells G, Shea B, O'Connell D, et al. The Newcastle-Ottawa Scale (NOS) for assessing the quality of nonrandomised studies in meta-analyses 2009 [Available from: http://www.ohri.ca/programs/clinical_epidemiology/oxford.asp. accessed August 15th 2016.
12. Higgins JPT, Green S. Cochrane handbook for systematic reviews of interventions version 5.1.0 [updated March 2011] 2011 [Available from: http://www.cochrane-handbook.org.
13. Group LoEW. The Oxford 2011 levels of evidence: Oxford centre for evidence-based medicine Oxford, UK, 2011.
14. Ho PM, Peterson PN, Masoudi FA. Evaluating the evidence: is there a rigid hierarchy? *Circulation* 2008;118(16):1675-84. doi: 10.1161/CIRCULATIONAHA.107.721357
15. Pearce KL, Sufrinko A, Lau BC, et al. Near Point of Convergence After a Sport-Related Concussion: Measurement Reliability and Relationship to Neurocognitive Impairment and Symptoms. *Am J Sports Med* 2015;43(12):3055-61.
16. Seidman DH, Burlingame J, Yousif LR, et al. Evaluation of the King-Devick test as a concussion screening tool in high school football players. *J Neurol Sci* 2015;356(1-2):97-101.
17. Broglio SP, Ferrara MS, Sopiarz K, et al. Reliable change of the sensory organization test. *Clin J Sport Med* 2008;18(2):148-54.

18. Cavanaugh JT, Guskiewicz KM, Giuliani C, et al. Detecting altered postural control after cerebral concussion in athletes with normal postural stability. *Br J Sports Med* 2005;39(11):805-11.
19. Fazio VC, Lovell MR, Pardini JE, et al. The relation between post concussion symptoms and neurocognitive performance in concussed athletes. *NeuroRehabilitation* 2007;22(3):207-16.
20. Furman GR, Lin C-C, Bellanca JL, et al. Comparison of the balance accelerometer measure and balance error scoring system in adolescent concussions in sports. *Am J Sports Med* 2013;41(6):1404-10.
21. Lovell MR, Collins MW, Iverson GL, et al. Grade 1 or "Ding" Concussions in High School Athletes. *Am J Sports Med* 2004;32(1):47-54.
22. Maddocks D, Saling M. Neuropsychological deficits following concussion. *Brain Inj* 1996;10(2):99-103.
23. McClincy MP, Lovell MR, Pardini J, et al. Recovery from sports concussion in high school and collegiate athletes. *Brain Inj* 2006;20(1):33-39.
24. Murray NG, Ambati VNP, Contreras MM, et al. Assessment of oculomotor control and balance post-concussion: A preliminary study for a novel approach to concussion management. *Brain Inj* 2014;28(4):496-503.
25. Pearce AJ, Hoy K, Rogers MA, et al. Acute motor, neurocognitive and neurophysiological change following concussion injury in Australian amateur football. A prospective multimodal investigation. *J Sci Med Sport* 2015;18(5):500-06.
26. Schatz P, Pardini JE, Lovell MR, et al. Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol* 2006;21(1):91-99.
27. Schatz P, Robertshaw S. Comparing post-concussive neurocognitive test data to normative data presents risks for under-classifying "above average" athletes. *Arch Clin Neuropsychol* 2014;29(7):625-32.
28. Tsushima WT, Shirakawa N, Geling O. Neurocognitive functioning and symptom reporting of high school athletes following a single concussion. *Applied Neuropsychology: Child* 2013;2(1):13-16.
29. Van Kampen DA, Lovell MR, Pardini JE, et al. The "value added" of neurocognitive testing after sports-related concussion. *Am J Sports Med* 2006;34(10):1630-35.
30. Broglio SP, Macciocchi SN, Ferrara MS. Sensitivity of the concussion assessment battery. *Neurosurgery* 2007;60(6):1050-57.
31. Cavanaugh JT, Guskiewicz KM, Giuliani C, et al. Recovery of postural control after cerebral concussion: New insights using approximate entropy. *J Athl Training* 2006;41(3):305-13.
32. Covassin T, Elbin RJ, Nakayama Y. Tracking neurocognitive performance following concussion in high school athletes. *Phys Sportsmed* 2010;38(4):87-93.
33. Echlin PS, Skopelja EN, Worsley R, et al. A prospective study of physician-observed concussion during a varsity university ice hockey season: incidence and neuropsychological changes. Part 2 of 4. *Neurosurg Focus* 2012;33(6):E2-11.
34. Eckner JT, Kutcher JS, Richardson JK. Effect of Concussion on Clinically Measured Reaction Time in 9 NCAA Division I Collegiate Athletes: A Preliminary Study. *PM and R* 2011;3(3):212-18.
35. Fuller GW, Kemp SP, Decq P. The International Rugby Board (IRB) Pitch Side Concussion Assessment trial: a pilot test accuracy study. *Br J Sports Med* 2015;49(8):529-35.
36. Lau BC, Collins MW, Lovell MR. Sensitivity and specificity of subacute computerized neurocognitive testing and symptom evaluation in predicting outcomes after sports-related concussion. *Am J Sports Med* 2011;39(6):1209-16.

37. Parsons TD, Notebaert AJ, Shields EW, et al. Application of reliable change indices to computerized neuropsychological measures of concussion. *Int J Neurosci* 2009;119(4):492-507.
38. Pedersen HA, Ferraro FR, Himle M, et al. Neuropsychological factors related to college ice hockey concussions. *Am J Alzheimers Dis Other Demen* 2014;29(3):201-04.
39. Broglio SP, Sosnoff JJ, Ferrara MS. The relationship of athlete-reported concussion symptoms and objective measures of neurocognitive function and postural control. *Clin J Sport Med* 2009;19(5):377-82.
40. Graves BS. University Football Players, Postural Stability, and Concussions. *J Strength Cond Res* 2016;30(2):579-83.
41. Houston MN, Bay RC, Valovich McLeod TC. The relationship between post-injury measures of cognition, balance, symptom reports and health-related quality-of-life in adolescent athletes with concussion. *Brain Inj* 2016;30(7):891-98.
42. Iverson GL, Gaetz M, Lovell MR, et al. Relation between subjective fogginess and neuropsychological testing following concussion. *J Int Neuropsychol Soc* 2004;10(6):904-06.
43. Louey AG, Cromer JA, Schembri AJ, et al. Detecting cognitive impairment after concussion: sensitivity of change from baseline and normative data methods using the CogSport/Axon cognitive test battery. *Arch Clin Neuropsychol* 2014;29(5):432-41.
44. Lovell MR, Iverson GL, Collins MW, et al. Measurement of symptoms following sports-related concussion: Reliability and normative data for the post-concussion scale. *Appl Neuropsychol* 2006;13(3):166-74.
45. Maddocks DL, Dicker GD, Saling MM. The assessment of orientation following concussion in athletes. *Clin J Sport Med* 1995;5(1):32-35.
46. Makdissi M, Collie A, Maruff P, et al. Computerized cognitive assessment of concussion in Australian rules football - abstract. In Sports Medicine Australia, 2001: a sports medicine odyssey: challenges, controversies and change: Australian Conference of Science and Medicine in Sport 23-27 October 2001, Perth, WA, Dickson, ACT, Sports Medicine Australia, c2001, p51. ;2001.
47. McCrea M, Kelly JP, Randolph C, et al. Immediate neurocognitive effects of concussion. *Neurosurgery* 2002;50(5):1032-2.
48. Putukian M, Echemendia R, Dettwiler-Danspeckgruber A, et al. Prospective clinical assessment using sideline concussion assessment tool-2 testing in the evaluation of sport-related concussion in college athletes. *Clin J Sport Med* 2015;25(1):36-42.
49. Register-Mihalik JK, Guskiewicz KM, Mihalik JP, et al. Reliable change, sensitivity, and specificity of a multidimensional concussion assessment battery: Implications for caution in clinical practice. *J Head Trauma Rehabil* 2013;28(4):274-83.
50. Schmidt JD, Register-Mihalik JK, Mihalik JP, et al. Identifying Impairments after concussion: normative data versus individualized baselines. *Med Sci Sports Exerc* 2012;44(9):1621-8. doi: 10.1249/MSS.0b013e318258a9fb [published Online First: 2012/04/25]
51. McCrory P. Scat3. *Br J Sports Med* 2013;47(5):259-59 1p.
52. Collins MW, Iverson GL, Lovell MR, et al. On-field predictors of neuropsychological and symptom deficit following sports-related concussion. *Clin J Sport Med* 2003;13(4):222-29.
53. Gardner A, Shores EA, Batchelor J, et al. Diagnostic efficiency of imPACT and cogsport in concussed rugby union players who have not undergone baseline neurocognitive testing. *Appl Neuropsychol* 2012;19(2):90-97.
54. Honaker JA, Lester HF, Patterson JN, et al. Examining postconcussion symptoms of dizziness and imbalance on neurocognitive performance in collegiate football players. *Otol Neurotol* 2014;35(6):1111-17.

55. Iverson GL, Lovell MR, Collins MW. Interpreting Change on ImPACT Following Sport Concussion. *Clin Neuropsychol* 2003;17(4):460-67.
56. Lau BC, Collins MW, Lovell MR. Cutoff scores in neurocognitive testing and symptom clusters that predict protracted recovery from concussions in high school athletes. *Neurosurgery* 2012;70(2):371-79.
57. Collie A, Makdissi M, Maruff P, et al. Cognition in the days following concussion: Comparison of symptomatic versus asymptomatic athletes. *J Neurol Neurosurg Psychiatry* 2006;77(2):241-45.
58. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute Effects and Recovery Time Following Concussion in Collegiate Football Players: The NCAA Concussion Study. *J Am Med Assoc* 2003;290(19):2556-63.
59. Pellman EI, Powell JW, Viano DC, et al. Concussion in Professional Football: Epidemiological Features of Game Injuries and Review of the Literature - Part 3. *Neurosurgery* 2004;54(1):81-96.
60. Weintraub A, Mellins CA, Warne P, et al. Patterns and Correlates of Serostatus Disclosure to Sexual Partners by Perinatally-Infected Adolescents and Young Adults. *AIDS Behav* 2017;21(1):129-40. doi: 10.1007/s10461-016-1337-6
61. Bruce DA, Schut L, Sutton LN. Brain and cervical spine injuries occurring during organized sports activities in children and adolescents. *Clin Sports Med* 1982;1(3):495-514.
62. Guskiewicz KM, Weaver NL, Padua DA, et al. Epidemiology of concussion in collegiate and high school football players. *Am J Sports Med* 2000;28(5):643-50 8p.
63. Delaney JS, Lacroix VJ, Gagne C, et al. Concussions among university football and soccer players: A pilot study. *Clin J Sport Med* 2001;11(4):234-40.
64. Gessel LM, Fields SK, Collins CL, et al. Concussions among United States high school and collegiate athletes. *J Athl Training* 2007;42(4):495-503 9p.
65. Harmon KG, Drezner JA, Gammons M, et al. American Medical Society for Sports Medicine position statement: concussion in sport. *Br J Sports Med* 2013;47(1):15-26. doi: 10.1136/bjsports-2012-091941 [published Online First: 2012/12/18]
66. Chin EY, Nelson LD, Barr WB, et al. Reliability and Validity of the Sport Concussion Assessment Tool-3 (SCAT3) in High School and Collegiate Athletes. *Am J Sports Med* 2016
67. Zasler ND. Sports concussion headache. *Brain Inj* 2015;29(2):207-20.
68. McDevitt J, Appiah-Kubi KO, Tierney R, et al. Vestibular and Oculomotor Assessments May Increase Accuracy of Subacute Concussion Assessment. *Int J Sports Med* 2016
69. Anzalone AJ, Blueitt D, Case T, et al. A Positive Vestibular/Ocular Motor Screening (VOMS) Is Associated With Increased Recovery Time After Sports-Related Concussion in Youth and Adolescent Athletes. *Am J Sports Med* 2017;45(2):474-79. doi: 10.1177/0363546516668624
70. Collins MW, Field M, Lovell MR, et al. Relationship between postconcussion headache and neuropsychological test performance in high school athletes. *Am J Sports Med* 2003;31(2):168-73. doi: 10.1177/03635465030310020301
71. Nashner LM, Black FO, Wall C, 3rd. Adaptation to altered support and visual conditions during stance: patients with vestibular deficits. *J Neurosci* 1982;2(5):536-44.
72. Lau BC, Kontos AP, Collins MW, et al. Which on-field signs/symptoms predict protracted recovery from sport-related concussion among high school football players? *Am J Sports Med* 2011;39(11):2311-18.
73. Arshad Q, Roberts RE, Ahmad H, et al. Patients with chronic dizziness following traumatic head injury typically have multiple diagnoses involving combined peripheral and central vestibular dysfunction. *Clin Neurol Neurosurg* 2017;155:17-19. doi: 10.1016/j.clineuro.2017.01.021

74. Benson BW, Meeuwisse WH, Rizos J, et al. A prospective study of concussions among National Hockey League players during regular season games: The NHL-NHLPA Concussion Program. *CMAJ* 2011;183(8):905-11.
75. Hartvigsen J, Boyle E, Cassidy JD, et al. Mild traumatic brain injury after motor vehicle collisions: what are the symptoms and who treats them? A population-based 1-year inception cohort study. *Arch Phys Med Rehabil* 2014;95(3 Suppl):S286-94. doi: 10.1016/j.apmr.2013.07.029
76. Marshall CM, Vernon H, Leddy JJ, et al. The role of the cervical spine in post-concussion syndrome. *Phys Sportsmed* 2015;43(3):274-84. doi: 10.1080/00913847.2015.1064301
77. Fine MS, Lum PS, Brokaw EB, et al. Dynamic motor tracking is sensitive to subacute mTBI. *Exp Brain Res* 2016;234(11):3173-84. doi: 10.1007/s00221-016-4714-5
78. Resch JE, McCrea MA, Cullum CM. Computerized neurocognitive testing in the management of sport-related concussion: An update. *Neuropsychol Rev* 2013;23(4):335-49.
79. Guskiewicz KM, Ross SE, Marshall SW. Postural Stability and Neuropsychological Deficits After Concussion in Collegiate Athletes. *J Athl Training* 2001;36(3):263-73.
80. Echemendia RJB, S. P.; Davis, G. A.; Guskiewicz, K.; Hayden, K. A.; Leddy, J.; Meehan, W.; Putukian, M.; Sullivan, S.J.; McCrory, P. What tests and measures should be added to the SCAT3 and related tests to improve their reliability, sensitivity and/or specificity in sideline concussion diagnosis? A systematic Review. *Br J Sports Med* 2017;Supplement on Concussion:in press.
81. Murray N, Salvatore A, Powell D, et al. Reliability and validity evidence of multiple balance assessments in athletes with a concussion. *J Athl Train* 2014;49(4):540-9. doi: 10.4085/1062-6050-49.3.32 [published Online First: 2014/06/17]
82. NeuroCom. A division of Natus. Setting the standard in balance and mobility. Sensory organization test. [Available from: http://www.resourcesonbalance.com/neurocom/protocols/sensoryImpairment/SOT.aspx accessed January 6th 2016.
83. Pellman EJ, Lovell MR, Viano DC, et al. Concussion in professional football: Neuropsychological testing - Part 6. *Neurosurgery* 2004;55(6):1290-303.
84. Schmidt JD, Guskiewicz KM, Mihalik JP, et al. Does visual performance influence head impact severity among high school football athletes? *Clin J Sport Med* 2015;25(6):494-501.